Eco-DAS VIII
Symposium Proceedings

Eco-DAS VIII Chapter 1, 2010, 1-16

Climate and anthropogenic change in aquatic environments: a cross ecosystem perspective

Julie E. Keister[1], D. Lani Pascual[2]*, Jessica L. Clasen[3], Kristine N. Hopfensperger[4], Noreen Kelly[5], Joel K. Llopiz[6], Serena M. Moseman[7], and Laura E. Petes[8]*

[1]School of Oceanography, University of Washington, Seattle, Washington 98195
[2]Department of Earth Sciences, Indiana University – Purdue University, Indianapolis, Indiana 46202
[3]Zoology, University of British Columbia, Vancouver, British Columbia, Canada V6T IZ4
[4]Department of Biological Sciences, Northern Kentucky University, Highland Heights, KY 41099
[5]Department of Biology, York University, Toronto, Ontario, Canada M3J 1P3
[6]Division of Marine Biology and Fisheries, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149
[7]Biology Department, Boston College, Chestnut Hill, MA 02467
[8]AAAS Science & Technology Fellow, NOAA Climate Program Office, Silver Spring, MD 20910

Abstract

In an effort to foster collaboration among researchers across diverse ecosystems, a group of early career scientists whose interests span the aquatic sciences, convened at the University of Hawai'i to participate in the 2008 Eco-DAS symposium. During a break out session of the symposium in which participants were charged with discussing how to best approach mitigation of climate and anthropogenic threats to aquatic ecosystems, participants concluded that effective mitigation will depend upon prioritizing threats across ecosystems. These priorities were documented using a thought experiment in which participants defined their ecosystem of expertise, and then ranked the highest-priority threats to them. Results revealed that marine (open ocean, deep sea, coastal oceans, and rocky intertidal) researchers ranked climate-related impacts (i.e., temperature and ocean acidification) as the highest priority threats whereas estuarine, marsh, wetland, stream, and lake/reservoir researchers ranked the direct anthropogenic impacts of land-use change and nutrient inputs (eutrophication) highest. With such a diverse group, it became apparent that working across ecosystems is limited by issues ranging from a lack of large-scale, long-term monitoring to provide baseline data, to broader questions of how changes in one ecosystem cascade across interconnected ecosystems. Here we summarize the discussions, offer insight into the rankings for specific ecosystems, and propose ideas of how past, current, and future research can be used to support a cross-ecosystem perspective on climate and anthropogenic change.

Climate and anthropogenic changes are altering aquatic ecosystems around the globe, in some areas with devastating consequences. Mitigating the impacts of those changes (or "threats") in a time frame that preserves aquatic systems will require management strategies that bridge local, regional, and global needs. But the path toward such integrated management is not clear: many studies on climate and other anthropogenically forced ecosystem changes have been conducted within specific ecosystems, but few have crossed aquatic ecosystem boundaries to provide insight to the relative importance of changes over broad scales. The desire to dismantle the conceptual boundaries that discipline-based science has built among ecosystems has highlighted the need to for a new, more integrated approach to observing, measuring, and predicting ecosystem changes due to overarching threats such as climate change (Loreau 2010; Caliman et al. 2010).

Here we report the dominant climate and anthropogenic threats to aquatic ecosystems as synthesized by a group of experts in the aquatic sciences. Our goal is to identify the

*Corresponding author: E-mail: jkeister@u.washington.edu

Acknowledgments

We thank Betsy Bancroft, Daniel "Dino" Marshalonis, and Daniel Sobota for their participation in the breakout session and subsequent discussions that formed the basis of this chapter. We also thank the Eco-DAS conveners; the National Science Foundation and Office of Naval Research for funding the symposium; and two reviewers whose anonymous comments improved the final manuscript.

Publication was supported by NSF award OCE0812838 to P.F. Kemp
ISBN: 978-0-9845591-1-4, DOI: 10.4319/ecodas.2010.978-0-9845591-1-4.1

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **Climate and anthropogenic change in aquatic environments: a cross ecosystem perspective**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **School of Oceanography ,University of Washington, ,Seattle,WA,98195**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

Publication was supported by NSF award OCE0812838 to P.F. Kemp ISBN: 978-0-9845591-1-4, DOI: 10.4319/ecodas.2010.978-0-9845591-1-4.1

14. ABSTRACT

In an effort to foster collaboration among researchers across diverse ecosystems, a group of early career scientists whose interests span the aquatic sciences, convened at the University of Hawai?i to participate in the 2008 Eco-DAS symposium. During a break out session of the symposium in which participants were charged with discussing how to best approach mitigation of climate and anthropogenic threats to aquatic ecosystems participants concluded that effective mitigation will depend upon prioritizing threats across ecosystems. These priorities were documented using a thought experiment in which participants defined their ecosystem of expertise, and then ranked the highest-priority threats to them. Results revealed that marine (open ocean, deep sea, coastal oceans, and rocky intertidal) researchers ranked climate-related impacts (i.e., temperature and ocean acidification) as the highest priority threats whereas estuarine, marsh, wetland, stream, and lake/reservoir researchers ranked the direct anthropogenic impacts of land-use change and nutrient inputs (eutrophication) highest. With such a diverse group, it became apparent that working across ecosystems is limited by issues ranging from a lack of large-scale, long-term monitoring to provide baseline data, to broader questions of how changes in one ecosystem cascade across interconnected ecosystems. Here we summarize the discussions, offer insight into the rankings for specific ecosystems, and propose ideas of how past, current, and future research can be used to support a cross-ecosystem perspective on climate and anthropogenic change.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Public Release**	**16**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

threats that have the broadest reaching impacts on aquatic ecosystems to inform scientists and managers of where to focus their research and management efforts. We explore commonalities across differing freshwater-to-marine ecosystems, define the prominent threats to several model aquatic ecosystems, and explore the biases inherent in creating such a synthesis. We conclude with a summary of where gaps exist in the current knowledge and areas where scientific breakthroughs may substantially contribute to filling those gaps.

A group of 13 early-career scientists representing diverse backgrounds within the aquatic sciences, with expertise ranging from high alpine lake ecosystems to the open ocean, and disciplines from geochemistry to zoology, convened during the 2008 Eco-DAS symposium to discuss mitigation priorities and strategies. Each scientist identified the dominant environmental threats to the ecosystem of their expertise, then subjectively ranked the top three (Table 1). The threats were consolidated into a feasible number of categories and grouped into 'Anthropogenic' and 'Climate Change' impacts. These groups were intended to differentiate acute, localized stressors such as eutrophication and land-use changes ('Anthropogenic' effects) from the chronic, large-scale effects of increased global atmospheric CO_2 concentration ('Climate' effects). Finally, the scientists attempted to identify the factors that have the greatest impacts across all aquatic ecosystems.

As a group, the scientists had no preconceived expectation of which factors may arise as the most widespread threats, but many expected that those they perceived as strongest in their system would also be important in others. However, the primary threats that were identified across ecosystems differed as widely as the systems themselves. Furthermore, instead of uncovering a few ubiquitously important threats, a compelling pattern was revealed. Moving from the open ocean to inland lakes, the highest-ranked threats shifted from those driven by large-scale, global climate change to those associated with regional, anthropogenically driven changes. Open ocean and coastal scientists ranked concerns of changing global temperature highest while scientists working in nearland or inland ecosystems ranked concerns of anthropogenic changes to the landscape (namely, land-use change and nutrient inputs) highest.

Whereas somewhat intuitive in hindsight, this unexpected result spurred excited discussion on the reason for, and implications of, the observed pattern. The ecosystems discussed (Table 1) differ in their fundamental properties, influences, and functions. However, if ecosystems act independently of each other, with unique external influences, such a clear pattern would likely not have emerged. Instead, the shift in 'threats' across systems corresponds to the proximity to humans: inland and coastal systems appear to be more susceptible to direct anthropogenic influences than the coastal seas or open ocean. This indicates that human alteration is more visible, more acute, and/or has greater impact than the indirect human-driven changes caused by global CO_2 increase. However, the spatial scales of the study environments also vary, gradating from smaller scales (e.g., streams and lakes) to the largest (the open ocean), as do the spatial scales of the impacts, with land-based anthropogenic changes having smaller spatial footprints compared to atmospherically driven changes. Similarly, the time scales of environmental influence on the systems are also likely to vary, with changes affecting smaller systems more rapidly than the larger, perhaps better buffered, systems in which low-frequency variability dominates. For example, the ocean has long been believed to dilute anthropogenic influences such as pollution and eutrophication compared with smaller systems, leading to a lag in response and poorly understood impacts of such impacts on the larger systems. Not until inputs reach some critical level in the ocean are they recognized as problematic; until that point, they are likely to remain under-studied.

To expand and verify results of the rankings, all 40 Eco-DAS symposium conveners and participants were surveyed for their expert rankings, and these rankings were compared against recent publication trends. The results of the survey were similar to the initial assessments. All six open ocean researchers ranked global temperature change as the greatest threat to their system; all six ranked ocean acidification as second or third, followed by over-harvesting. One open ocean researcher with an interest in the effects of micro-plastics on the environment ranked pollutants/contaminants among the top three threats. Nearshore coastal oceanographers ranked nutrient inputs and global temperature changes as the top two threats. Changes in precipitation and run-off and invasive species were also highly ranked. The sole coral reef expert ranked nutrient inputs, global temperatures, and sedimentation as the largest factors effecting reefs.

When we compare the rankings from our survey to a literature search of publications that addressed threats within each ecosystem using *Thomson Reuters Web of Knowledge* online citation database in January 2009, we found that the Eco-DAS participants' rankings were mirrored by the number of literature publications. Open ocean and coastal ocean researchers published more studies on the effects of global threats (i.e., climate change), specifically, temperature change (30.5% of the articles) and sea level rise (7.5%) (Fig. 1). Ocean acidification, a major concern for the Eco-DAS participants has not long been widely recognized as a threat to aquatic systems, and was not well-represented in the literature. In 2009, 278 "ocean" articles were associated with acidification; however, in 2010, this number had more than doubled to 651, demonstrating that our survey results reflected the current perceptions of broader science community.

Eight of nine estuarine scientists ranked nutrient loading and land- use changes as the top two threats to estuaries, with sedimentation, physical modification, precipitation, and global temperature changes also highly ranked. Interestingly, while a literature search for "land use change" in estuary or intertidal systems resulted in few publications (2.1% of the

Table 1. The dominant threats to aquatic ecosystems driven by anthropogenic and global climate change. The top three threats to each ecosystem as subjectively ranked by symposium break-out group participants within their field of expertise are shown. Number of respondents representing each ecosystem is given in parentheses. 'Total number of rankings' are the total number of scientists (out of 40) across all disciplines that ranked an impact among the top three threats to their ecosystem. FW = Freshwater.

	Open ocean	Deep sea	Continental shelves	Rocky intertidal	Coastal ocean	Estuaries	Tidal FW marshes	FW wetlands	Streams	FW Lakes	Total number of rankings
Local Anthropogenic Impacts											
Land-use Change						1	1	1	1	1	19
Nutrient Changes					2	2		3	2	2	26
Sedimentation											5
Acid Rain											3
Physical modification		1									7
Pollution											7
Invasive species				3							6
Over-harvesting	2		3								6
Global Climate Impacts:											
Temperature	1	3	1	1	1						16
Precipitation					3		3	2	3	3	11
Acidification	3	2	2								9
Sea Level Rise				2		3	2				3
UV radiation											2
Number of expert participants:	(6)	(1)	(1)	(1)	(6)	(9)	(2)	(1)	(4)	(9)	(40)

total), some of the indirect effects of land-use change ("pollution," "nutrients," and "sedimentation") accounted for 52.3% (Fig. 1). Overharvesting, global temperature changes, and invasive species were among the top three impacts ranked by a few estuarine researchers in our study. Publication volumes concur: 13.6% of searched articles on these ecosystems address overharvesting, global temperature change, and invasive species (Fig. 1). Surprisingly, ocean acidification was not ranked among the top three threats by any of the estuarine scientists, nor was it a highly published topic; only 6.9% of papers on intertidal and estuarine systems were associated with the key word "acidification." Overall, these findings demonstrate that Eco-DAS scientists and the greater research community consider both local and global changes as threats to estuarine ecosystems.

The majority of freshwater lakes, wetland, and stream specialists rated nutrient loading and precipitation changes most highly, with land-use changes very important to streams, and invasive species important in lakes. These perceptions differed slightly from the literature: whereas Eco-DAS participants highly ranked "nutrient changes" over "pollution," publication volumes were greater for "pollution." This is likely because pollution research could include several types of pollutants (e.g., pesticides, emerging contaminants [pharmaceuticals], and nutrients). Land-use change (5%) fell behind physical modification (7.7%; Fig. 1). Only one stream ecologist and one alpine lakes expert ranked global temperature increases among the top threats to their ecosystem. Changes in UV radiation concerned two lake researchers. Surprisingly, acid rain, which was the poster child of destructive anthropogenic ecosystem impacts in the 1970s and 1980s, was only highly ranked by two of ten lake ecologists, possibly reflecting improved conditions over the past decades and/or a shift in funding as the focus moves toward understanding different threats to these ecosystems. Whereas Eco-DAS participant opinions differed from those of the general freshwater research community in the particulars, both the survey and literature search results indicate that localized impacts are perceived as the greatest threats to inland freshwaters.

The following boxes describe several aquatic ecosystems in more detail, and the dominant climate and anthropogenic threats to them are explored. These descriptions, written by some of the scientists who participated in the symposium, provide perspectives on the wide-ranging problems facing ecosystem managers and policy-makers.

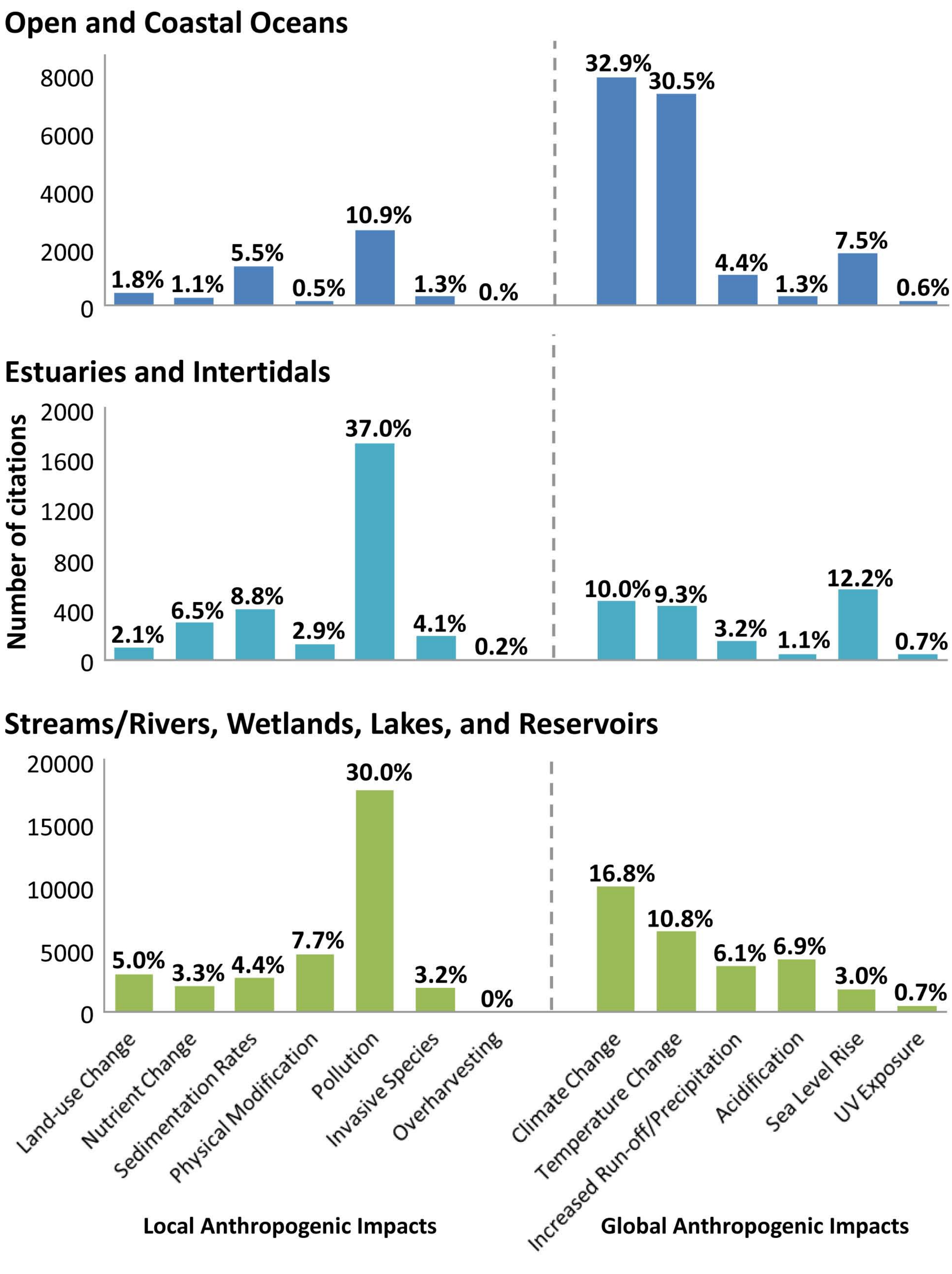


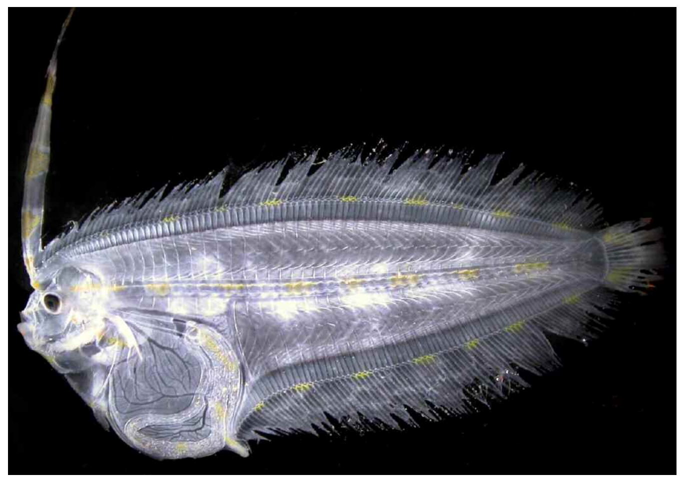
Fig. 1. Literature search results from key word searches of threats within each ecosystem using the *Thomson Reuters Web of Knowledge* online citation database in January 2009.

Box 1. Open Ocean (Joel Llopiz)

The world's largest aquatic habitat is the vast open ocean regions that are generally characterized by stable environmental conditions, but low diversity and productivity compared with other aquatic ecosystems. Because of their distance from land, intuition may suggest that open ocean ecosystems are not highly impacted by anthropogenic influences. Whereas this might be generally true of direct anthropogenic impacts, slight yet rapid changes occurring in the open ocean due to climate-related influences are having significant impacts on the ecosystems. Additionally, the open ocean supports a significant portion of the world's fisheries, many of which have been critically impacted by unsustainable harvest levels (Botsford et al. 1997).

Our survey of scientists who study the open ocean indicated clear agreement that the major threats to these ecosystems have their roots in global atmospheric CO_2 increases (i.e., global warming) and overharvesting, as opposed to the more land-based local stressors such as nutrient loading, sedimentation, and pollution. The three top-ranked threats to open ocean ecosystems were the pervasive and far-reaching effects of increasing ocean temperatures and acidification, with overharvesting of marine organisms also of primary concern. These results support those of Halpern et al. (2007) who conducted formal international surveys of marine ecosystem experts and concluded that global temperature changes and overharvesting constitute the greatest threats to open ocean ecosystems.

Temperature increases lead to expansions and contractions of species habitat ranges and alter physiological processes, both of which can translate to significant disruptions in the ecological functioning of ecosystems (e.g., Harley et al. 2006; Clasen et al. 2010, this volume). Ocean acidification, often regarded as the greatest threat to marine ecosystems, is due to increased levels of dissolved CO_2 in the ocean (a direct result of increased atmospheric CO_2 from human activities), which in turn, lowers the pH of the water and the availability of carbonate ions (CO_3^{2-}) to organisms that rely on calcium carbonate. This can result in decreased growth rates of ecologically important organisms such as pteropods, coccolithophores, foraminifera, corals, coralline algae, mollusks, and echinoderms (Kleypas et al. 2006; Fabry et al. 2008). Additionally, if waters become under saturated with respect to calcium carbonate, complete mortality of these organisms may occur, leading to profound and cascading ecosystem effects. Similarly, the removal of species through overharvesting is having major impacts on marine ecosystems (e.g., Frank et al. 2005; Myers and Worm 2003; Clasen et al. 2010, this volume), largely due to disruptions to the trophic structure in these systems.



Open ocean ecosystems are inhabited by a diversity of organisms, from bacteria to whales, which are all threatened by rising temperatures and ocean acidification. Among the threatened organisms are the planktonic larvae of many ecologically and economically important fishes and invertebrates that recruit to benthic or coastal habitats, such as this 15-mm larval flounder. (Photo: C. Guigand)

Box 2. Deep-Sea Ecosystems (Noreen Kelly)

The largest ecosystem on the planet, the deep-sea (defined as depths below the permanent thermocline) comprises approximately 60% of the surface of the Earth and makes a vital contribution to a number of ecosystem functions in the global ocean, including nutrient recycling, carbon burial, and controls on ocean chemistry. Whereas the deep-sea contains multiple distinct habitats, from the rocky mid-ocean ridges, submarine canyons, trenches, and seamounts, to the island-like chemoautotrophic cold seeps, hydrothermal vents, and whale-falls, the most extensive habitats are the sediment-covered continental slopes and abyssal plains, which cover vast areas of the deep-sea floor and extend unbroken for thousands of kilometers (Gage and Tyler 1992). Productivity and biological rates (e.g., growth, colonization) vary among these habitats, with low rates occurring in sediment-covered slopes and abyssal plains and higher rates occurring in the hard-bottomed island habitats, resulting in a variable response of deep-sea communities to anthropogenic impacts and climate change.

Two recent reviews identifying the principal anthropogenic disturbances to deep-sea ecosystems highlight deep-sea fishing, oil, gas and mineral extraction, and climate change as the most immediate threats (Glover and Smith 2003; Smith et al. 2008). Most deep-sea fisheries are unsustainable and are likely to have an immediate impact on those communities that experience low rates of natural disturbance and slow rates of growth and colonization (Watling and Norse 1998; Devine et al. 2006). With the exception of chemoautotrophic communities, organisms in the deep sea are typically food-limited, and rely on sinking organic material produced in surface waters (Rex and Etter 2010). Thus, climate or anthropogenic impacts that alter rates of primary production in the upper ocean will indirectly alter the composition and structure of deep-sea benthic communities (e.g., Ruhl and Smith 2004). Global climate change may also have the most wide-spread effects on the deep-sea biota due to shifts in temperature (Danovaro et al. 2004), changing ocean chemistry (Orr et al. 2005), and/or global changes in the deep-ocean thermohaline circulation (Yasuhara et al. 2008). Furthermore, escalating pressure on terrestrial disposal sites may lead to increased disposal of waste such as sewage, dredge spoil, radioactive by-products, industrially produced pollutants, and carbon dioxide in the deep-sea, negatively impacting community composition and function around disposal sites (Tyler 2003). Whereas oil and gas exploration and extraction are predicted to impact deep continental slope communities due to the accumulation of contaminated drill cuttings, the mining of other geological resources from the seafloor (e.g., manganese nodule mining) would negatively impact abyssal plain communities via removal of the substrate and redeposition of suspended sediments (Smith et al. 2008).

Although the initial effects of anthropogenic stressors are likely to impact deep-sea communities only on local scales (0–100 km), the lack of distinct barriers between vast areas of the deep-sea could spread such impacts across regional (100–1000 km) and basin (1000–10 000 km) scales (Glover and Smith 2003). In addition, deep-sea communities located close to continental shelves and slopes are likely to experience the effects of multiple stressors simultaneously, compounding and/or magnifying their impacts on these communities. Given the paucity of studies on deep-sea compared with other aquatic habitats, accurately predicting the impacts of anthropogenic disturbance and stressors on deep-sea communities is presently challenging. Many future ecosystem changes are likely to go undetected.

Box 3. Coastal Upwelling Ecosystems (Julie E. Keister)

Coastal upwelling systems are among the most productive regions of the world's ocean. The four large Eastern Boundary Current upwelling systems (EBCs)—the California Current, Humboldt Current, Benguela Current, and Canary Current—together account for more than 20% of the global fishery production (Pauly and Christensen 1995) and 11% of the total global new production (Chavez and Toggweiler 1995), although they comprise less than 2% of the total surface ocean area. The productivity of these systems depends upon strong alongshore winds which drive offshore surface transport and replacement of the surface water with upwelled, nutrient-rich deep water. The high nutrient inputs then support rich communities of plankton, which in turn support large populations of fish, sea birds, and marine mammals.

Although many direct anthropogenic influences such as pollutants, overharvesting, and nutrient inputs have deleterious effects upon upwelling ecosystems, none have yet had as obviously catastrophic impacts as have climate-related changes in wind patterns. A clear example of the large impact climate can have on these ecosystems is the collapse of the pelagic food web in the California Current System in 2005. That year, the seasonal upwelling winds that typically begin in late spring were delayed by > 6 weeks (Kosro et al. 2006; Pierce et al. 2006). As a result, a warm surface layer capped the nutrient-rich deep water and prevented springtime production (Thomas and Brickley 2006), which resulted in altered zooplankton distributions (Mackas et al. 2006), fisheries collapses (Brodeur et al. 2006), breeding failure of planktivorous seabirds (Sydeman et al. 2006), and changes in gray whale and California sea lion foraging strategies (Weise et al. 2006; Newell and Cowles 2006).

Coastal upwelling winds are driven by the atmospheric pressure gradients set up by large-scale patterns of heating and cooling (Bakun 1990). It is not clear from model and observational data how coastal upwelling winds will be impacted by global warming. Recent empirical evidence from the Humboldt, Canary, and California Current systems indicates increasing trends in upwelling winds (Mendelssohn and Schwing 2002; Vargas et al. 2007; Bakun and Weeks 2008), but a decreasing trend has been reported in the Benguela Current system (Peard 2007 as cited in Bakun et al. 2010). Climate models are also in disagreement (Mote and Mantua 2002; Snyder et al. 2003), indicating the difficulty in predicting future impacts.

Counter-intuitively, increased upwelling, and nutrient-delivery may not lead to increased ecosystem productivity (Bakun et al. 2010). Coastal populations are sensitive to offshore advection, particularly zooplankton, which have multi-week life cycles. During strong upwelling, coastal zooplankton can be transported hundreds of kilometers offshore in eddies and upwelling filaments (Keister et al. 2009). Increased upwelling can result in spatial mismatch between zooplankton and phytoplankton populations if cross-shelf transport times decrease relative to life cycle duration (Botsford et al. 2003). This plankton mismatch can lead to increased occurrences of hypoxic events: unchecked, large phytoplankton blooms sink and support increased bacterial decomposition and hypoxia in deep waters, leading to further decreases in overall ecosystem production with increased upwelling.

The primary direct anthropogenic threats to coastal upwelling ecosystems are the large, economically important fisheries that they support. Many fished populations are declining, resulting in cascading effects such as altered predator-prey interactions and changes in nutrient cycling that may lead to fundamental changes in ecosystem functioning. In the Benguela Current, where overfishing has depressed forage fish abundances, nuisance jellyfish blooms are increasingly common as they are released from competition for their zooplankton prey (Richardson et al. 2009; Lynam et al. 2006).

Recently, concern about the effects of ocean acidification on coastal upwelling systems has escalated with the finding that acidified water is upwelling in the California Current (Feely et al. 2008), decades prior to predictions. Many calcifying zooplankton such as crustaceans, bivalves, echinoderms, and pteropods are critical components of the food web. Global mean surface ocean pH has declined by ~0.1 units from pre-industrial levels and is predicted to decline another 0.2-0.3 units by the end of this century (Caldeira and Wickett 2003). These changes are likely to impact the ecosystem in ways that are not yet understood.

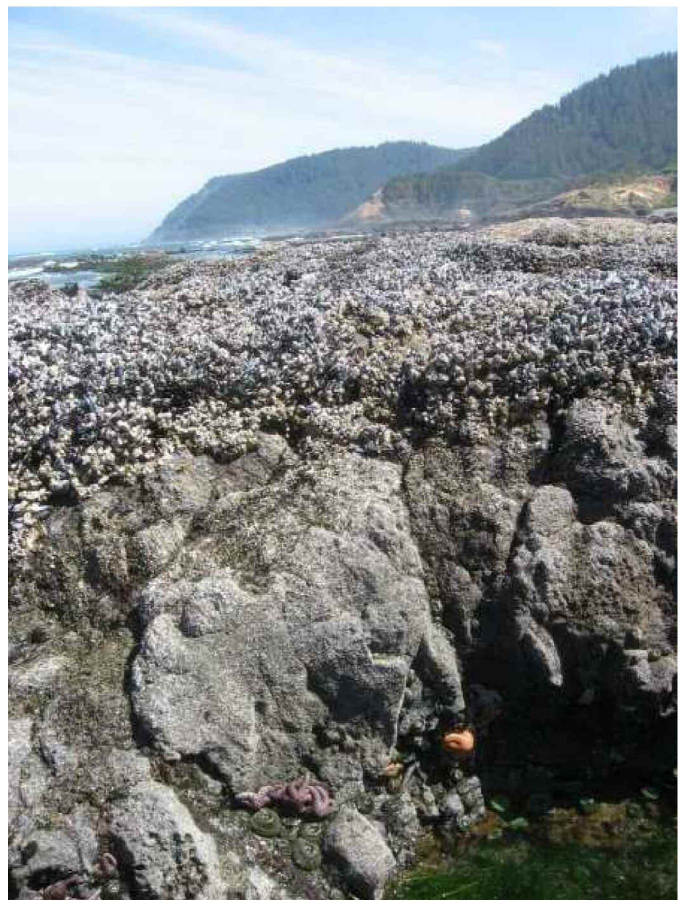
A school of Pacific White–sided dolphin roughen the ocean waters as they feed in the California Current Upwelling System off Oregon. Climate-related changes in wind patterns and ocean temperatures are predicted to alter the productivity of these rich and diverse ecosystems. (Photo: J. Keister, April 2002)

Box 4. Rocky Intertidal Zones (Laura E. Petes)

Rocky intertidal zones exist at the margin of the land and the sea. These coastal ecosystems are exposed to the air during low tide and are submerged in water at high tide. By nature, they are vulnerable to stressors from both terrestrial and marine environments. Their proximity to land makes them susceptible to direct, local anthropogenic impacts including coastal development, pollution, sedimentation, and overharvesting (Thompson et al. 2002). However, the stressor ranked as number one in importance in our survey was global temperature change. Because these ecosystems are exposed to both air and water, temperature change in either will impact intertidal organisms. Stress typically increases along a vertical gradient in the rocky intertidal zone because the organisms that live in the high intertidal zone are exposed to air for longer periods of time during low tide than organisms in the low intertidal zone. Many intertidal species are already living at, or close to, their physiological tolerance limits for air temperature, and therefore even small increases in air temperature can lead to mortality events in the high intertidal zone (e.g., Petes et al. 2007). Sessile, benthic organisms are particularly at risk because they are unable to move to avoid thermal stress.

Whereas the impacts of sea level rise on rocky intertidal zones are less well-understood than the impacts of temperature, this stressor was ranked as second in importance. Many intertidal predators, such as sea stars and crabs, forage primarily during high tide when the intertidal zone is submerged. The lower vertical limit of species distribution in the intertidal zone is primarily set by the distance that predators can migrate upwards during a single high-tide period. With sea level rise under climate change, predators will be able to migrate higher in the intertidal zone to feed, removing the spatial refuge of prey in the low intertidal zone. As a result, the lower edge of the intertidal zone will likely migrate upwards as these prey are removed by predators. If mortality of organisms in the high intertidal zone occurs due to increases in air temperature, and mortality of organisms in the low intertidal zone occurs due to predation associated with sea level rise, a "squeeze" (*sensu* Harley et al. 2006) or vertical compression of the intertidal zone will occur under climate change.

Invasive species were ranked as third in importance for rocky intertidal zones. The most common method of introduction in marine ecosystems is ship ballast water, which can transport up to 10,000 species at a time (Carlton 1999). New species interactions as a result of introductions can alter the trophic structure of native communities; invasive species often outcompete native species for space and resources (Grosholz 2002). Invasions of rocky shores by species including the European green crab (*Carcinus maenas*; e.g., Trussell et al. 2003) and the invasive "Dead man's fingers" seaweed (*Codium fragile*; e.g., Trowbridge 1995) have dramatically altered community structure of the native ecosystems. Under future human population growth, globalization, and increases in transportation, it is likely that more successful introductions will occur. In addition, climate change will likely lead to poleward range expansion of invasive species that prefer warmer temperatures.



Diverse benthic taxa including sea stars, mussels, limpets, and anemones cling to rocks awaiting the return of the cool ocean waters in the rocky intertidal zone at Strawberry Hill, Cape Perpetua, Oregon. (Photo: L. Petes, May 2009)

Box 5. Estuaries and Coasts (Serena Moseman-Valtierra)

Coastal marine wetlands, such as salt marshes, link land and sea, stabilize coasts, serve as nurseries for waterfowl and fish, and are active sites of biogeochemical transformations. Vascular plants dominate the landscape but algal producers and cyanobacteria also contribute to high productivity of the system. The responses of ecosystems such as wetlands and estuaries to climate and anthropogenic impacts are likely to be substantial because of their close proximity to burgeoning coastal human populations. Furthermore, the consequences of changes in these systems extend beyond their boundaries due to their transitional position at the interface of terrestrial, freshwater, and marine realms (Ewel et al. 2001).

Nutrient loading is one of the greatest threats to estuaries; eutrophication has negatively impacted more than 50% of estuaries in the U.S. alone (Boesch 2002; Howarth et al. 2002). But nutrient loading is often accompanied by, or results from, land use, run-off, and sedimentation changes. The tight relationships among these local anthropogenic impacts highlights the growing need to address interactions among multiple threats in, and beyond, these ecosystems (Ineson et al. 2004). A manipulative experiment in a salt marsh of Tijuana Estuary by Moseman-Valtierra et al. (2010) offers an example of the interactions between land-use and nitrogen changes. Sediment inputs from the surrounding watershed alone showed no direct effect on nitrogen fixation in this estuary, but when sedimentation occurred in combination with nutrient-loading, porewater NH_4^+ concentrations remained significantly higher for longer periods of time than where nutrient inputs occurred without sedimentation. This suggests that long-term changes in coastal ecosystems due to nutrient loading may be exacerbated by devegetation and other associated changes.

Differences in threat responses, and therefore management priorities, exist between temperate and tropical ecosystems, the former of which have dominated the ecological literature (Petenon and Pivello 2008). When top threats to estuaries were ranked separately for temperate versus tropical systems in our study, nutrient loading and land-use were top priorities only for the temperate systems, while precipitation/run-off and sedimentation were considered to be important impacts on tropical estuaries. Climate and human impacts are likely to increase in tropical relative to temperate estuaries as human population increases over the next century. A better understanding of how ecosystem function varies with latitude would be helpful for predicting their potential responses to changing climate (Bertness and Ewanchuk 2002).

Sea level rise due to global warming was highly ranked as a threat to coastal systems in our survey; one third of estuarine researchers ranked it as a top threat. Sea level rise will have its greatest impact in systems where rates of accretion are not sufficient to maintain elevation of the ecosystem, resulting in loss of habitat. However, recent studies have suggested that elevated CO_2 concentrations may stimulate marsh accretion, potentially helping to offset negative effects of sea level rise (Langley et al. 2009).

Invasive species were not highly ranked as threats to estuaries in our study, possibly because their impacts are perceived to work on smaller temporal and spatial scales than those of other threats. Nonetheless, invasive species are known to have dramatic, rapid impacts on estuarine ecosystems (Crooks 2002). Small-scale impacts may have consequences for the resilience and recovery of ecosystems on larger scales, perhaps by influencing which habitats persist to face longer term perturbations. Small-scale stressors like invasions may also be greatly exacerbated by larger scale changes in climate (Scavia et al. 2002). The cross-scale implication of threats thus warrants further consideration in research and management of coastal ecosystems.

Box 6. Tidal freshwater marsh (Kristine N. Hopfensperger)

Tidal freshwater marshes (TFWM) are situated in the landscape between upstream activities and land-uses, such as agriculture and urban centers, and downstream estuaries. TFWMs receive tidal activity similarly to salt marshes, but without the influence of salinity, thereby resulting in diverse and productive plant communities (Parker and Leck 1985). Because of their location and diversity, TFWMs have been called the kidneys of the landscape as they are capable of filtering out and removing a large percent of nutrients that pass through them (Odum 1988). Not only are tidal freshwater marshes productive, diverse, and efficient at improving water quality, they are responsible for many human-valued functions including providing wildlife habitat for a diverse number of terrestrial and aquatic species (Odum et al. 1984), stabilizing water supplies through amelioration of floods and drought, and absorbing impacts from large storms through shoreline stabilization and attenuation of tidal energy (Mitsch and Gosselink 2000).

Perceptions of Eco-DAS participants, supported by the literature, showed that (1) land-use change and (2) sea level rise are the most important threats to the TFWM ecosystem. Land-use change is an important threat to tidal freshwater marsh ecosystems. Historically, TFWM area was lost from direct conversion to different land-uses, such as agriculture or urban areas (Wilson et al. 2007). For example, the Chesapeake Bay watershed in the eastern U.S. has lost 50% of its wetlands due to draining and filling activities (Dahl 1990). However, any factor that changes the elevation or hydrology of a TFWM (e.g., deforestation or channelization) can result in a changed species composition (Leck and Simpson 1987; Pasternack et al. 2000). Fossil records from a TFWM near Baltimore, Maryland, USA revealed that after a submerged aquatic vegetation bed remained stable for over 1500 years, the rapid sediment efflux from broad habitat changes along the watershed hydrologic gradient from the 1700s through the 1900s led to a dramatic conversion to drier, forested communities (Hilgartner and Brush 2006).

Currently, losses of TFWMs are due to a combination of local anthropogenic impacts and sea level rise, the second most influential stressor to TFWMs. In general, tidal marshes should be able to keep up with sea level rise by either landward movement of the wetlands or sediment accretion (Callaway et al. 1996; Craft et al. 2009). However, urban development and the hardening of shorelines inhibit landward movement along many coastlines. In other areas, sediment accretion rates do not keep up with sea level rise where sediment inputs are reduced by direct anthropogenic changes (e.g., dams) or climate-related changes (e.g., droughts). In addition, the loss of marsh vegetation by water inundation from sea level rise can result in a feedback of decreased sediment accretion (Stevenson et al. 1986; Morris 2006; Craft 2007; Neubauer 2008).

Sea level rise can also have detrimental effects on TFWMs through increased salinity and sulfide concentrations (US EPA 2008), which can dramatically change the vegetation communities and biogeochemical cycling within the ecosystem. Furthermore, the decrease in freshwater inputs to tidal wetlands due to an increase in human demand for water and droughts may amplify salinity induced stress to TFWMs (Martin and Shaffer 2005; McKee et al. 2004; Craft et al. 2009). Increased salinity reduces the ability of a TFWM to be a nitrogen (N) sink by allowing sulfate-reducing bacteria to outcompete nitrifying bacteria (Craft et al. 2009). Increases in salinity and sulfide decrease plant uptake of N and negatively influence plant recruitment, reproduction, growth, and survival of macrophytes (Koch et al. 1990; Crain et al. 2004; Callaway et al. 2007).

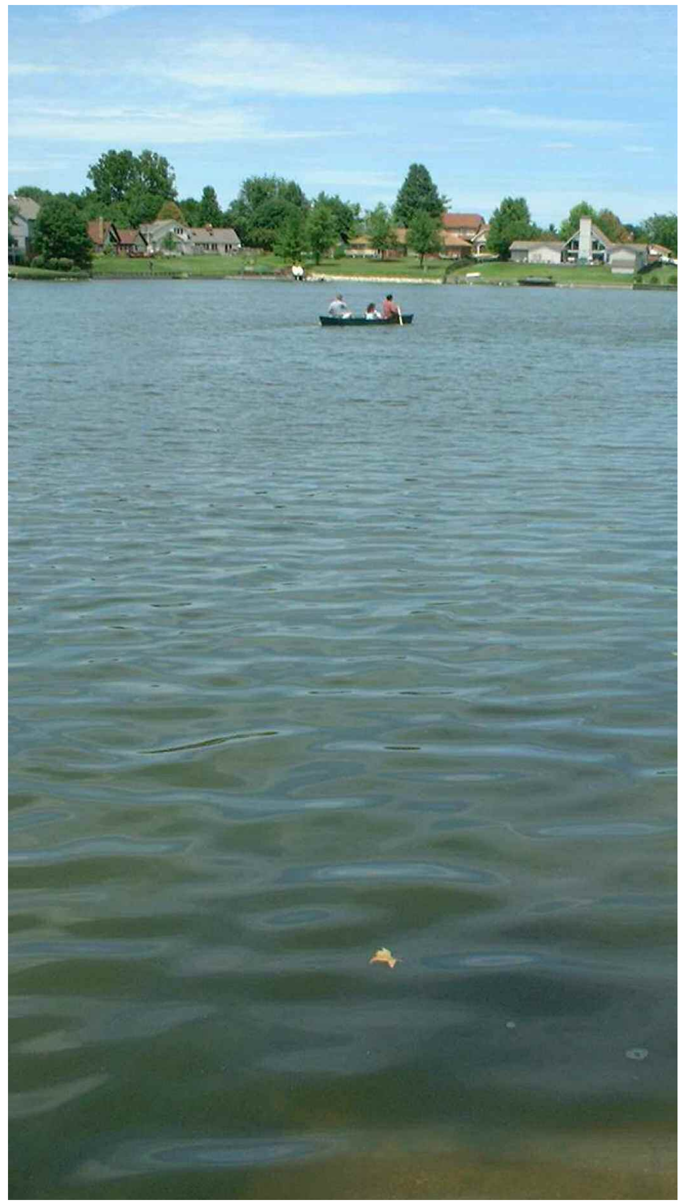
A common misconception is that N-loading is a significant stressor in TFWMs, yet TFWMs are ideal ecosystems to handle excess N. Nitrogen-loading in estuaries can lead to harmful algal blooms, anoxic zones, and a loss of biotic life (Engel and Thayer 1998). But in TFWMs, macrophytes slow water movement and allow for short-term removal of N through plant assimilation, and long-term N removal by burial and denitrification (Brantley et al. 2008). In fact, plant productivity, N mineralization, microbial immobilization, and coupled nitrification-denitrification are largely independent of water column N-loading, and instead, are dependent on intra-system N-cycling within the sediment (Neubauer et al. 2005). TFWMs continue to be a net sink of N even when the sediment contains more N than the incoming water (Neubauer et al. 2005) and nitrate concentrations increase (Kana et al. 1998).

Dyke Marsh Preserve (National Park Service) in Belle Haven, Virginia, exemplifies the high biodiversity and spatial microtopographic variation of tidal freshwater marshes. (Photo: Kristine N. Hopfensperger, May 2004)

Box 7. Freshwater Lakes and Reservoirs (Jessica Clasen)

Surface freshwater environments are inland bodies of water that include lotic environments (e.g., rivers and streams) and lentic environments (e.g., wetlands, lakes, and reservoirs). All of these habitats have characteristically low concentrations of salt and other dissolved solids (salinity < 0.5). Less than 3% of the water on Earth is freshwater, with lakes accounting for approximately 0.4% of the freshwater. Of this 0.4%, approximately half is found in small lakes and reservoirs (i.e., lakes other than the Great Lakes and Lake Baikal). Whereas lakes and reservoirs account for a very small percentage of the total water on Earth (<0.005%), these diverse environments are the interface between terrestrial and aquatic ecosystems, making them essential water resources for life on this planet.

Within the 2008 Eco-DAS participants, 16 studied freshwater habitats, including streams, lakes, reservoirs, high elevation lakes, marshes, and wetlands. Analysis of the survey results from these participants readily identified several common threats to freshwaters, including both land-use change (ranked number one by 22% of participants) and invasive species (11%). One high-elevation limnologist indicated that their system is most threatened by changing precipitation and run-off patterns. The majority (56%) of freshwater researchers identified nutrient loading as the most eminent threat for freshwater ecosystems.



The murky waters of Grassy Creek Reservoir in Greenwood, Indiana, illustrate the local anthropogenic impacts of nutrient loading caused by the application of lawn fertilizers to small lakes and reservoirs in urban and suburban areas. (Photo: D. L. Pascual, May 2004)

Nutrient loading is often defined as the quantity of nutrients (nitrogen and/or phosphorous) entering an ecosystem over time. High nutrient loading rates typically result in the eutrophication of an ecosystem. Eutrophication has been a topic of concern for several decades; in North America, the highly publicized poor water quality of Lake Erie in the 1960s and early 1970s ignited interest in the process of eutrophication. Schindler's 1977 paper in the journal *Science* on the evolution of phosphorus limitation in lakes is widely considered to be the seminal paper on the effect of increased nutrient loading rates on lake ecosystems. He and his colleagues at the Experimental Lakes Area demonstrated that increasing phosphorous concentration directly leads to cultural eutrophication (Schindler 1977). Thirty-two years later, nutrient loading and eutrophication are still active research areas.

Despite numerous research studies and policy initiatives that addressed eutrophication issues, including the United States' Clean Water Act of 1972, nutrient loading is still of concern in the U.S. and around the world. The monetary impact of lake eutrophication in the U.S. alone has been estimated at $2.2 billion dollars annually (Dodds et al. 2009). Wetzel (1992) stated that the "fresh waters of the world are collectively experiencing markedly accelerating rates of qualitative and quantitative degradation." The 2005 Millennium Ecosystem Assessment (MEA) report identified eutrophication/nutrient pollution as having had very high impacts on lake ecosystems over the last century and see them as continuing issues for the Americans, Asia, and Europe, predicting that these factors will have a progressively stronger impact on lakes in the future (Vörösmarty et al. 2005).

These summaries of recent research, and the concerns of researchers in these specific ecosystems, further demonstrate that a major limitation of a cross-ecosystem approach to understanding anthropogenic change is the conceptual delineation among ecosystems which are, inherently, connected. Because we conceptualize that ecosystems have distinct boundaries; we must infer the causality and consequences of changes that occur within that specific ecosystem to the ecosystems to which it is connected. Several new approaches to understanding ecosystems have emerged in the past 10 years: Ecological Stoichiometry (Sterner and Elser 2002), Biodiversity and Ecosystem Functioning (BEF; Loreau et al. 2001; Loreau 2010; Caliman et al. 2010), and Ecosystem Services (Daily and Matson 2008). Each of these approaches seek to understand how ecosystems function through the transfer of energy and elements (Ecological Stoichiometry), by looking at the interactions between species and their abiotic environment (BEF), or by the products that each ecosystem provides to human populations. These approaches may provide a start to developing a cross-ecosystem approach: If we can use these approaches to understand and identify the major processes and functions of an ecosystem, then perhaps, we can extend these understandings to look across interconnected ecosystems.

In recognition of these limitations of how we study ecosystems, many questions remained following the discussion, including questions on our understanding of environmental changes within ecosystems, the interactions among ecosystems, and how to objectively determine science and funding priorities to address the problems. The discussion was concluded with the question: Where will breakthroughs come? Participants discussed three areas of research that may produce breakthroughs in understanding the effects of climate and anthropogenic impacts across aquatic systems.

Large-scale modeling—Although interdisciplinary, observational studies that span multiple connected ecosystems such as the National Science Foundation's Long-Term Ecological Research (LTER) program have considerably increased our understanding of ecosystem linkages, realistically, it is impractical to conduct such intensive field studies in all systems. Studies that look at the linkages among ecosystem components, such as biogeochemistry, productivity, nutrient cycling, and trophic interactions are rare. Given the deficiency of such integrated studies, large-scale modeling may be the most practical method to explore the effects of ecosystem changes. These models can provide breakthroughs by enabling researchers to identify deficiencies in datasets, and by helping focus future research.

Long-term monitoring and baseline data—Long-term ecosystem monitoring is critical for developing baseline datasets upon which change can be evaluated. But establishing stable funding for monitoring efforts is increasingly difficult, particularly in under-studied and economically disadvantaged regions. Increasingly, citizen groups are becoming involved in monitoring studies as local interest in ecosystem conservation increases. Additionally, primary and secondary schools are incorporating local monitoring as part of experiential learning curricula. Future organization of such grassroots research across different ecosystems could lead to significant breakthroughs in our understanding of ecosystem changes.

Developing a common metric—Because it is difficult to evaluate change across and among interconnected ecosystems, the concept of a *cross-ecosystem function and/or process* was seen as the most promising metric. Whereas this is specifically defined by each of the aforementioned approaches, participants concluded that an ecosystem function or service be any function or service that one ecosystem provides to the ones to which it is connected. As Loreau et al. (2001) noted, ecosystem change, especially changes to biodiversity, are difficult to observe and measure as many are epiphenomenon, driven by a combination factors. Therefore, participants proposed that cross-ecosystem function be a simple overarching process, which results in the continued function of the connected ecosystem. As an example, the "service" of a stream may be to provide a lake or estuary with clean, pollution-free water; the service of the estuary may be to provide nursery areas for larval stages of marine fish. If some function within an ecosystem fails (e.g., the stream is polluted), it may affect the service to adjacent systems (e.g., polluted water enters the estuary), potentially resulting in failure of the connected ecosystem's service (e.g., mortality of fish larvae in the estuary).

Cross-ecosystem services may therefore be useful, practical metrics upon which cascading effects of anthropogenic or climate impacts can be evaluated. Such research could be used to identify *Indicator Ecosystem Services*, the service(s) that are most important to the linked ecosystems, and/or are most sensitive to change. Linkages among ecosystem components, such as the biogeochemistry, productivity, nutrient cycling, and trophic interactions can be built in a way that is meaningful across ecosystems. These indicator services could then inform managers of how to track changes caused by climate or anthropogenic impacts, and of where to focus research and mitigation efforts.

However, this undertaking must take into consideration the limitations in our current understanding. Notably, our literature search showed that there is a disparate number of research studies on freshwater and marine environments compared with intertidal and estuarine ecosystems, that freshwater ecosystem research is lacking in studies on global anthropogenic threats such as global temperature change and UV exposure, and that marine ecosystem research is lacking in studies on invasive species, acidification, and UV exposure (Fig. 1). Caliman et al. (2010) noted that research on the relationships between biodiversity and abiotic ecosystem function in aquatic ecosystems (especially ocean ecosystems) has fallen behind such research efforts in terrestrial ecosystems. Because each ecosystem and subdiscipline researcher prioritizes threats based on the inherent biases of creating conceptual delin-

eations among ecosystems and ecosystem processes (e.g., physical hydrology, biogeochemical cycles, and trophic interactions), a more integrative approach is needed to truly understand ecosystems in relationship to each other as they undergo anthropogenic change. Therefore, we echo Caliman and coolleague's (2010) call for more integrative research (such as BEF) in response to the multifaceted threats upon (inland and coastal) aquatic ecosystems. Finally, we call for a central system in which all data across aquatic ecosystems can be compiled and analyzed for long-term trends. From small studies done by classes, educational groups, and local interest groups, to comprehensive monitoring studies, these data are valuable for documenting historical baselines from which current and future trends can be measured.

Potential study biases—Results of this survey-based study must be interpreted with caution. Several biases potentially affect the expert opinions of the relative importance of threats to their study systems. In particular, biases derived from differences in individual backgrounds and research focus areas can be strong. Here, the unique representation by experts from diverse aquatic ecosystems provides an uncommon perspective to the study, and helped mediate the influence of individual bias. Nevertheless, those biases were likely important in shaping the findings presented.

Biases derived from phenomena that are not so easily recognized may also be important. The largest of those may derive from the phenomenon of 'shifting baselines' in which an individual's perception of the state of an ecosystem is based on their recent experience rather than on a long-term, historical perspective. 'Fluctuating baselines' can work to increase or decrease the perceived importance of any particular impact. For example, decadal-scale climate variability causes low-frequency temperature cycles upon which relatively low-amplitude long-term trends due to global warming may be imposed. Individuals raised during a 'warm regime' may not recognize the impact of global warming over their lifetime if a 'cold regime' dominates the latter part of their lives; whereas individuals raised during 'cold regimes' may experience dramatic warming over their lives.

Finally, funding agencies are instrumental in shaping perceptions of the important factors affecting ecosystems. Historical funding priorities have shaped our knowledge of the status of ecosystems, while current funding priorities may focus on particular environmental changes that are 'hot topics' but not of central scientific importance. This bias may vary among countries or regions, and should be carefully considered when allocating research effort in an attempt to mitigate the factors that may have not only severe long-term ecosystem impacts, but also broad-scale, global impacts.

References

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. Science 247:198-201 [doi:10.1126/science.247.4939.198].

———, and S. J. Weeks. 2008. The marine ecosystem off Peru: What are the secrets of its fishery productivity and what might its future hold? Prog. Oceanogr. 79:290-299 [doi:10.1016/j.pocean.2008.10.027].

———, D. B. Field, A. Redondo-Rodriguez, and S. J. Weeks. 2010. Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. Glob. Change Biol. 16:1213-1228 [doi:10.1111/j.1365-2486.2009.02094.x].

Bertness, M. D., and P. J. Ewanchuk. 2002. Latitudinal and climate-driven variation in the strength and nature of biological interactions in New England salt marshes. Oecologia 132:392-401 [doi:10.1007/s00442-002-0972-y].

Boesch, D. F. 2002. Challenges and opportunities for science in reducing nutrient over-enrichment of coastal ecosystems. Estuaries 25:886-900 [doi:10.1007/BF02804914].

Botsford, L. W., J. C. Castilla, and C. H. Peterson. 1997. The management of fisheries and marine ecosystems. Science 277:509-515 [doi:10.1126/science.277.5325.509].

———, C. A. Lawrence, E. P. Dever, A. Hastings, and J. Largier. 2003. Wind strength and biological productivity in upwelling systems: an idealized study. Fish. Oceanogr. 12:245-259 [doi:10.1046/j.1365-2419.2003.00265.x].

Brantley, C. G., J. W. Day, Jr., R. R. Lane, E. Hyfield, J. N. Day, and J.- Y. Ko. 2008. Primary production, nutrient dynamics, and accretion of a coastal freshwater forested wetland assimilation system in Louisiana. Ecol. Eng. 34:7-22 [doi:10.1016/j.ecoleng.2008.05.004].

Brodeur, R. D., S. Ralston, R. L. Emmett, M. Trudel, T. D. Auth, and A. J. Phillips. 2006. Anomalous pelagic nekton abundance, distribution, and apparent recruitment in the northern California Current in 2004 and 2005. Geophys. Res. Lett.. 33 [doi:10.1029/2006GL026614].

Caldeira, K., and M. E. Wickett. 2003. Anthropogenic carbon and ocean pH. Nature 425:365-365 [doi:10.1038/425365a].

Caliman, A., A. F. Pires, F. A. Esteves, R. L. Bozelli, and V. F. Farjalla. 2010. The prominence of and biases in biodiversity and ecosystem functioning research. Biodivers. Conserv. 19(3):651-664.

Callaway, J. C., J. A. Nyman, and R. D. Delaune. 1996. Sediment accretion in coastal wetlands: a review and a simulation model of processes. Curr. Topics Wetland Biogeochem. 2:2-23.

———, V. T. Parker, M. C. Vasey, and L. M. Schile. 2007. Emerging issues for the restoration of tidal marsh ecosystems in the context of predicted climate change. Madroño 54:234-248 [doi:10.3120/0024-9637(2007)54[234:EIFTRO]2.0.CO;2].

Carlton, J. T. 1999. The scale and ecological consequences of biological invasions in the world's oceans, p. 195-212. *In*: O. T. Sandlund, P. J. Schei, and Å. Viken [eds.], Invasive species and biodiversity management. Kluwer Academic Publishers.

Chavez, F. P., and J. R. Toggweiler. 1995. Physical estimates of

global new production: the upwelling contribution. Environ. Sci. Res. Rep. 18:313-320.

Clasen, J. L., J. K. Llopiz, C. E. H. Kissman, D. Marshalonis, and D. L. Pascual. 2010. The vulnerability of ecosystem trophic dynamics to anthropogenically induced environmental change: A comparative approach. *In* P. F. Kemp [ed.], Eco-DAS VIII Symposium Proceedings, p. 45-64.

Craft, C. 2007. Freshwater input structures soil properties, vertical accretion and nutrient accumulation of Georgia and U.S. tidal marshes. Limnol. Oceanogr. 52:1220-1230 [doi:10.4319/lo.2007.52.3.1220].

———, J. Clough, J. Ehman, S. Joye, R. Park, S. Pennings, H. Guo, and M. Machmuller. 2009. Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. Frontiers Ecol. Environ. 7:73-78 [doi:10.1890/070219].

Crain, C. M., B. R. Silliman, S. L. Bertness, and M. D. Bertness. 2004. Physical and biotic drivers of plant distribution across estuarine salinity gradients. Ecology 85:2539-2549 [doi:10.1890/03-0745].

Crooks, J. A. 2002. Characterizing ecosystem-level consequences of biological invasions: the role of ecosystem engineers. Oikos 97:153-166 [doi:10.1034/j.1600-0706.2002.970201.x].

Dahl, T. E. 1990. Wetlands losses in the United States 1780s to 1980s. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. Jamestown, ND: Northern Prairie Wildlife Research Center Online.

Daily, G. C., and P. A. Matson. 2008. Ecosystem services: From theory to implementation. Proc. Nat. Acad. Sci. U.S.A. 105(28): 9455-9456 [doi:10.1073/pnas.0804960105].

Danovaro, R., A. Dell'Anno, and A. Pusceddu. 2004. Biodiversity response to climate change in a warm deep sea. Ecol. Lett. 7:821-828 [doi:10.1111/j.1461-0248.2004.00634.x].

Devine, J. A., K. D. Baker, and R. L. Haedrich. 2006. Fisheries: deep-sea fishes qualify as endangered. Nature 439:29 [doi:10.1038/439029a].

Dodds, W. K., and others. 2009. Eutrophication of U.S. freshwaters: analysis of potential economic damages. Environ. Sci. Technol. 43:12-19 [doi:10.1021/es801217q].

Engel, D. W., and G. W Thayer. 1998. Effects of habitat alteration on blue crabs. J. Shellfish Res. 17:579-585.

Ewel, K. C. and others. 2001. Managing critical transition zones. Ecosystems 4:452-460 [doi:10.1007/s10021-001-0106-0].

Fabry, V. J., B. A. Seibel, R. A. Feely, and J. C. Orr. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES J. Mar. Sci. 65:414-432 [doi:10.1093/icesjms/fsn048].

Feely, R. A., C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales. 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf. Science 320:1490-1492 [doi:10.1126/science.1155676].

Frank, K. T., B. Petrie, J. S. Choi, and W. C. Leggett. 2005. Trophic cascades in a formerly cod-dominated ecosystem. Science 308:1621-1623 [doi:10.1126/science.1113075].

Gage, J. D., and P. A. Tyler. 1992. Deep-sea biology: a natural history of organisms at the deep-sea floor. Cambridge Univ. Press.

Glover, A. G., and C. R. Smith. 2003. The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. Environ. Conserv. 30:219-241 [doi:10.1017/S0376892903000225].

Grosholz, E. 2002. Ecological and evolutionary consequences of coastal invasions. Trends Ecol. Evol. 17:22-27 [doi:10.1016/S0169-5347(01)02358-8].

Halpern, B. S., K. A. Selkoe, F. Micheli, and C. V. Kappel. 2007. Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. Conserv. Biol. 21:1301-1315 [doi:10.1111/j.1523-1739.2007.00752.x].

Harley, C. D. G., and others. 2006. The impacts of climate change in coastal marine systems. Ecol. Lett. 9:228-241 [doi:10.1111/j.1461-0248.2005.00871.x].

Hilgartner, W. B., and G. S. Brush. 2006. Prehistoric habitat stability and post-settlement habitat change in a Chesapeake Bay freshwater tidal wetland, USA. Holocene 16:479-494 [doi:10.1191/0959683606hl938rp].

Howarth, R. W., A. Sharpley, and D. Walker. 2002. Sources of nutrient pollution to coastal waters in the United States: implications for achieving coastal water quality goals. Estuaries 25:656-676 [doi:10.1007/BF02804898].

Ineson, P., and others. 2004. Cascading effects of deforestation on ecosystem services across soils and freshwater and marine sediments, p. 225-248. *In*: D. H. Wall [ed.], Sustaining biodiversity and ecosystem services in soils and sediments. Island Press.

Kana, T. M., M. B. Sullivan, J. C. Cornwell, and K. M. Groszkowski. 1998. Denitrification in estuarine sediments determined by membrane inlet mass spectrometry. Limnol. Oceanogr. 43:334-339 [doi:10.4319/lo.1998.43.2.0334].

Keister, J. E., W. T. Peterson, and S. D. Pierce. 2009. Zooplankton distribution and cross-shelf transfer of carbon in an area of complex mesoscale circulation in the northern California Current. Deep-Sea Res. [doi:10.1016/j.dsr.2008.1009.1004].

Kleypas, J. A., R. A. Feely, V. J. Fabry, C. Langdon, C. L. Sabine, and L. L. Robbins. 2006. Impacts of ocean acidification on coral reefs and other marine calcifiers: a guide for future research, report of a workshop sponsored by NSF, NOAA, and the U.S. Geological Survey.

Koch, M. S., I. A. Mendelssohn, and K. L. McKee. 1990. Mechanism for the hydrogen sulfide-induced growth limitation in wetland macrophytes. Limnol. Oceanogr. 35:399-408 [doi:10.4319/lo.1990.35.2.0399].

Kosro, P. M., W. T. Peterson, B. M. Hickey, R. K. Shearman, and S. D. Pierce. 2006. Physical versus biological spring transition: 2005. Geophys. Res. Lett. 33 [doi:10.1029/2006GL027072].

Langley, J. A., K. L. Mckee, D. R. Cahoon, J. A. Cherry, and J.

P. Megonigal. 2009. Elevated CO_2 stimulates marsh elevation gain, counterbalancing sea-level rise. Proc. Nat. Acad. Sci. U.S.A. 106:6182-6186.

Leck, M. A., and R. L. Simpson. 1987. Seed bank of a freshwater tidal marsh: turnover and relationship to vegetation change. American Journal of Botany 74:360-370 [doi:10.2307/2443812].

Levin, L. A., and others. 2001. The function of marine critical transition zones and the importance of sediment biodiversity. Ecosystems 4:430-451 [doi:10.1007/s10021-001-0021-4].

Loreau, M. 2010. Linking biodiversity and ecosystems: towards a unifying ecological theory. Phil. Trans. Roy. Soc. Biol. Sci. 365:49-60 [doi:10.1098/rstb.2009.0155].

———, and others. 2001. Biodiversity and ecosystem functioning current knowledge and future challenges. Science 294(5543):804-808 [doi:10.1126/science.1064088].

Lynam, C. P. and others. 2006. Jellyfish overtake fish in a heavily fished ecosystem. Curr. Biol. 16: R492-R493 [doi:10.1016/j.cub.2006.06.018].

Mackas, D. L., W. T. Peterson, M. D. Ohman, and B. E. Lavaniegos. 2006. Zooplankton anomalies in the California Current system before and during the warm ocean conditions of 2005. Geophys. Res. Lett. 33 [doi:10.1029/2006GL027930].

Mendelssohn, R., and F. B. Schwing. 2002. Common and uncommon trends in SST and wind stress in the California and Peru-Chile Current Systems. Prog. Oceanogr. 53:141-162 [doi:10.1016/S0079-6611(02)00028-9].

Martin, S. B., and G. P. Shaffer. 2005. Sagittaria biomass partitioning relative to salinity, hydrologic regime, and substrate type: implications for plant distribution patterns in coastal Louisiana, USA. J. Coast. Res. 21:164-171.

McKee, K., I. A. Mendelssohn, and M. D. Materne. 2004. Acute salt marsh dieback in the Mississippi River deltaic plain: a drought induced phenomenon? Glob. Ecol. Biogeogr. 13:65-73 [doi:10.1111/j.1466-882X.2004.00075.x].

Mitsch, W. J., and J. G. Gosselink. 2000. Wetlands, 3rd ed. Wiley.

Morris, J. T. 2006. Competition among marsh macrophytes by means of geomorphological displacement in the intertidal zone. Estuar. Coast. Shelf Sci. 69:395-402 [doi:10.1016/j.ecss.2006.05.025].

Moseman-Valtierra, S. M., K. Armaiz-Nolla, and L. A. Levin. 2010. Wetland response to sedimentation and nitrogen loading: diversification and inhibition of nitrogen-fixing microbes. Ecol. Appl. 20:1556-1568 [doi:10.1890/08-1881.1].

Mote, P. W., and N. J. Mantua. 2002. Coastal upwelling in a warmer future. Geophys. Res. Lett. 29:2138 [doi:10.1029/2002gl016086].

Myers, R. A., and B. Worm. 2003. Rapid worldwide depletion of predatory fish communities. Nature 423:280-283 [doi:10.1038/nature01610].

Neubauer, S. C. 2008. Contributions of mineral and organic components to tidal freshwater marsh accretion. Estuar. Coast. Shelf Sci. 78:78-88 [doi:10.1016/j.ecss.2007.11.011].

———, I. C. Anderson, and B. B. Neikirk. 2005. Nitrogen cycling and ecosystem exchanges in a Virginia tidal freshwater marsh. Estuaries 28:909-922 [doi:10.1007/BF02696019].

Newell, C. L., and T. J. Cowles. 2006. Unusual gray whale *Eschrichtius robustus* feeding in the summer of 2005 off the central Oregon Coast. Geophys. Res. Lett. 33:L22S11 [doi:10.1029/2006gl027189].

Odum, W. E. 1988. Comparative ecology of tidal freshwater and salt marshes. Ann. Rev. Ecol. System. 19:147-176 [doi:10.1146/annurev.es.19.110188.001051].

Odum, W. E., T. J. Smith III, J. K. Hoover, and C. C. McIvor. 1984. The ecology of tidal freshwater marshes of the United States East Coast: a community profile. U.S. Fish and Wildlife Service Report FWS/OBS-83/17.

Orr, J. C., and others. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437:681-686 [doi:10.1038/nature04095].

Parker, V. T., and M. A. Leck. 1985. Relationships of seed banks to plant distribution patterns in a freshwater tidal wetland. Amer. J. Bot. 72:161-174 [doi:10.2307/2443543].

Pasternack, G. B., W. B. Hilgartner, and G. S. Brush. 2000. Biogeomorphology of an upper Chesapeake Bay river-mouth tidal freshwater marsh. Wetlands 20:520-537 [doi:10.1672/0277-5212(2000)020<0520:BOAUCB>2.0.CO;2].

Pauly, D., and V. Christensen. 1995. Primary production required to sustain global fisheries. Nature 374:255-257.

Peard, K. 2007. Seasonal and interannual variability of wind-driven upwelling at Luderitz, Manibia, Ph.D. thesis. Univ. of Cape Town.

Petenon, D., and V. R. Pivello. 2008. Invasive plants: representativeness of research from tropical countries in the global context. Natureza Conservacao 6:183-195.

Petes, L. E., B. A. Menge, and G. D. Murphy. 2007. Environmental stress decreases survival, growth, and reproduction in New Zealand mussels. J. Exp. Mar. Biol. Ecol. 351:83-91 [doi:10.1016/j.jembe.2007.06.025].

Pierce, S. D., J. A. Barth, R. E. Thomas, and G. W. Fleischer. 2006. Anomalously warm July 2005 in the northern California Current: Historical context and the significance of cumulative wind stress. Geophys. Res. Lett. 33 [doi:10.1029/2006GL027149].

Rex, M. A., and R. J. Etter. 2010. Deep-sea biodiversity: pattern and scale. Harvard Univ. Press.

Richardson, A. J., A. Bakun, G. C. Hays, and M. J. Gibbons. 2009. The jellyfish joyride: causes, consequences and management responses to a more gelatinous future. Trends Ecol. Evol. 24:312-322.

Ruhl, H. A., and K. L. Smith, Jr. 2004. Shifts in deep-sea community structure linked to climate and food supply. Science 305:513-515 [doi:10.1126/science.1099759].

Scavia, D., and others. 2002. Climate change impacts on US

coastal and marine ecosystems. Estuaries 25:149-164 [doi:10.1007/BF02691304].

Schindler, D. W. 1977. Evolution of phosphorous limitation in lakes. Science 195:260-262 [doi:10.1126/science.195.4275.260].

Smith, C. R., L. A. Levin, A. Koslow, P. A. Tyler, and A. G. Glover. 2008. The near future of the deep seafloor ecosystems, p. 334-351. *In*: N. Polunin [ed.], Aquatic ecosystems: trends and global prospects. Cambridge Univ. Press.

Snyder, M. A., L. C. Sloan, N. S. Diffenbaugh, and J. L. Bell. 2003. Future climate change and upwelling in the California Current. Geophys. Res. Lett. 30:1823 [doi:10.1029/2003GL017647].

Sterner, R. W., and J. J. Elser. 2002. Ecological Stoichiometry: the biology of elements from molecules to the biosphere. New Jersey, Princeton Univ. Press.

Stevenson, J. C., L. G. Ward, and M. S. Kearney. 1986. Vertical accretion in marshes with varying rates of sea level rise, p. 241-259. *In*: D. A. Wolfe [ed.], Estuarine variability. Academic Press.

Sydeman, W. J., and others. 2006. Planktivorous auklet Ptychoramphus aleuticus responses to ocean climate, 2005: Unusual atmospheric blocking? Geophys. Res. Lett. 33: L22S09 [doi:10.1029/2006GL026736].

Thomas, A. C., and P. Brickley. 2006. Satellite measurements of chlorophyll distribution during spring 2005 in the California Current. Geophys Res Let 33: L22S05 [doi:10.1029/2006gl026588].

Thompson, R. C., T. P. Crowe, and S. J. Hawkins. 2002. Rocky intertidal communities: past environmental changes, present status and predictions for the next 25 years. Environ. Conserv. 29:168-191 [doi:10.1017/S0376892902000115].

Trowbridge, C. D. 1995. Establishment of the green alga Codium fragile ssp. tomentosoides on New Zealand rocky shores: current distribution and invertebrate grazers. J. Ecol. 83:949-965 [doi:10.2307/2261177].

Trussell, G. C., P. J. Ewanchuk, and M. D. Bertness. 2003. Trait-mediated effects in rocky intertidal food chains: predator risk cues alter prey feeding rates. Ecology 84:629-640 [doi:10.1890/0012-9658(2003)084[0629:TMEIRI]2.0.CO;2].

Tyler, P. A. 2003. Disposal in the deep sea: analogue of nature or faux ami? Environ. Conserv. 30:26-39 [doi:10.1017/S037689290300002X].

Vargas, G., S. Pantoja, J. A. Rutllant, C. B. Lange, and L. Ortlieb. 2007. Enhancement of coastal upwelling and interdecadal ENSO-like variability in the Peru-Chile Current since late 19th century. Geophys. Res. Lett. 34: L13607 [doi:10.1029/2006gl028812].

Vörösmarty, C. J., C. Lévêque, and C. Revenga. 2005. Fresh water, p. 167-201. *In*: R. Hassan, R. Scholes, and N. Ash. [eds.], Ecosystems and human well-being: current state and trends, vol. 1. Island Press.

Watling, L., and E. A. Norse. 1998. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. Conserv. Biol. 12:1180-1197 [doi:10.1046/j.1523-1739.1998.0120061180.x].

Weise, M. J., D. P. Costa, and R. M. Kudela. 2006. Movement and diving behavior of male California sea lion (*Zalophus californianus*) during anomalous oceanographic conditions of 2005 compared to those of 2004. Geophys. Res. Lett. 33: L22S10 [doi:10.1029/2006gl027113].

Wetzel, R. G. 1992. Clean water: a fading resource. Hydrobiologia 243/244:21-30 [doi:10.1007/BF00007017].

Wilson, M. D., B. D. Watts, and D. F. Brinker. 2007. Status review of Chesapeake Bay marsh lands and breeding marsh birds. Waterbirds 30:122-137 [doi:10.1675/1524-4695(2007)030[0122:SROCBM]2.0.CO;2].

Yasuhara, M., T. M. Cronin, P. B. deMenocal, H. Okahashi, and B. K. Linsley. 2008. Abrupt climate change and collapse of deep-sea ecosystems. Proc. Nat. Acad. Sci. U.S.A. 105:1556-1560 [doi:10.1073/pnas.0705486105].